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ORIGINAL RESEARCH

CONCURRENT VALIDITY AND RELIABILITY OF 2D KINEMATIC ANALYSIS OF FRONTAL PLANE MOTION DURING RUNNING

Jennifer N. Maykut, PT, DPT, CSCS[1]
Jeffery A. Taylor-Haas, PT, DPT, OCS, CSCS[2]
Mark V. Paterno, PT, PhD, MBA, SCS, ATC[2]
Christopher A. DiCesare, MS[3]
Kevin R. Ford, PhD, FACSM[4]

ABSTRACT

Purpose: Three-dimensional motion analysis is the "gold standard" for evaluating kinematic variables during treadmill running. However, its use is limited by temporal and financial restraints. Therefore, the purpose of this study was to assess the concurrent validity and reliability of 2D video analysis for frontal plane kinematic variables during treadmill running.

Methods: Twenty-four healthy male and female collegiate cross-country runners completed a running protocol at a self-selected speed. Frontal plane kinematic data were collected using 3D and 2D motion analysis systems. Variables of interest included contralateral pelvic drop (CPD), peak hip adduction angle (HADD), and peak knee abduction angle (KABD). Pearson Product Correlation Coefficients were used to determine the relationship between the 3D and 2D systems for each variable. Intra-Class Correlation Coefficients (ICC) were used to assess intra-rater reliability of the user of the 2D software.

Results: The 2D testing method demonstrated excellent intra-rater reliability for peak HADD (ICCs: 0.951-0.963), peak CPD (0.958-0.966), and peak KABD (ICCs: 0.955-0.976). Moderate correlations between 2D and 3D measures of HADD on the left (0.539; $p = 0.007$) and the right (0.623; $p = 0.001$) and peak KABD on the left (0.541; $p = .006$) lower extremity were found. No statistically significant correlation of CPD was found between the 2D and 3D systems. The 2D measure of CPD had a strong correlation to the 2D assessment of HADD on both the left (0.801; $p = 0.0001$) and the right (0.746; $p = 0.0001$) extremity.

Conclusion: These findings and the ease of data capture using 2D software provide support for the utility of 2D video analysis in the evaluation of frontal plane variables, specifically HADD.

Level of evidence: 2B

Key words: 2D video analysis, contralateral pelvic drop, hip adduction, running

[1] Rehabilitation Division, OhioHealth Westerville Medical Campus, Westerville, OH, USA
[2] Occupational and Physical Therapy Division, Cincinnati Children's Hospital Medical Center, Cincinnati, OH, USA
[3] Sports Medicine, Cincinnati Children's Hospital Medical Center, Cincinnati, OH, USA
[4] Physical Therapy Division, High Point University, High Point, NC, USA

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CORRESPONDING AUTHOR
Jennifer Maykut, PT, DPT, CSCS
Rehabilitation Department, OhioHealth
Westerville Medical Campus
300 Polaris Parkway, Westerville, OH, 43082
E-mail: Jennifer.maykut@ohiohealth.com

INTRODUCTION

The incidence of lower extremity running injuries ranges from 19.4-79.3%.[1,2] The predominant location for injury is the knee, comprising 42.1% of all running-related injuries.[2,3] Patellofemoral Pain Syndrome (PFPS) is the most common running-related injury, followed closely by Iliotibial Band Syndrome (ITBS), plantar fasciitis, meniscal knee injury, and medial tibial stress syndrome.[3] Current evidence suggests links between altered lower extremity biomechanics and running-related injuries.[4,5] As both competitive and recreational running continues to grow in popularity, there is an ever-increasing need to examine individual running technique and running biomechanics with the goal of better informing injury prediction, prevention, and rehabilitation.

Standardized analyses of running gait offers an objective measure of multi-planar biomechanical risk factors that may contribute to injury in runners. Three frontal plane kinematic variables that are frequently analyzed clinically include contralateral pelvic drop, peak hip adduction angle, and peak knee abduction angle. All three variables have been extensively reported in the literature and have significant clinical implications with regards to injury rehabilitation and prevention in runners with a variety of diagnoses including PFPS[6–11], ITBS [9,12,13], and medial tibial stress syndrome.[14,15] It has been theorized that contralateral pelvic drop, hip adduction, and knee abduction play roles in abnormal lower extremity biomechanics affecting the entire lower extremity kinetic chain.[5,16] Specific biomechanical flaws, such as excessive or mistimed contralateral pelvic drop and knee abduction, along with femoral internal rotation, tibial external rotation, and foot pronation, have been theoretically linked to injury in a population of patients with PFPS.[17] Kinematically, excessive hip adduction and hip internal rotation in weight bearing causes the knee joint to move medially relative to the foot, which results in tibial abduction and increased foot pronation. The end result is increased knee abduction, also known as dynamic genu valgus.[16]

The gold standard for running gait analysis for both clinical and research purposes is three-dimensional (3D) motion-capture.[18] However, the use of 3D analysis imposes significant financial, spatial, and temporal costs. These concerns suggest the need for clinically applicable alternatives. The most commonly used clinical alternative to 3D analysis is two-dimensional (2D) techniques. Two-dimensional systems often involve the use of standard video cameras and software to conduct kinematic analyses. Although 2D video analysis offers a more feasible option for evaluating kinematics during dynamic movements, this method is not without limitations. One proposed limitation includes how fully 2D motion analysis can capture dynamic and complex multiple planar motions. Specifically, dynamic knee valgus, which is a composite measure of hip adduction, femoral internal rotation, and tibial external rotation, may not be best represented by a simplified 2D assessment in the frontal plane.

As a result of these concerns, there have been multiple studies evaluating the validity and reliability of 2D software during functional movements.[18–24] In regard to reliability, good within-day reliability (ICCs = 0.59-0.88) and good to excellent between-day reliability (ICCs = 0.72-0.91) on frontal plane projection angle (FPPA) measurements were found during single-leg squat and drop jump with single-leg landings.[21] FPPA has been examined as a way to analyze dynamic valgus and predict or screen for injuries of the lower extremity, specifically at the knee.[18,21–24] Excellent intra-rater reliability for 2D video analysis of hip adduction and knee valgus during single limb step downs[20] and moderate to high intra-rater reliability for knee valgus during performance tests[25] has been reported in the literature. In addition, Norris and Olsen found excellent inter-rater and intra-rater reliability for sagittal plane knee and hip flexion during mechanical lifting.[24]

The results regarding concurrent validity of 2D motion analysis are mixed. Moderate correlation exists between 2D and 3D motion systems in the frontal plane for side stepping and side jump motions.[18] However, 2D frontal plane kinematics of the knee during single-leg step down movements has been poorly correlated to 3D methods in the literature.[22] 2D analysis of knee and hip kinematics in the sagittal plane during mechanical lifting was reported to be valid ($r \geq 0.95$, $p = 0.01$).[24] In contrast to these results, the utility of the frontal plane projection angle (FPPA) during single-limb squats and single leg step downs was found to have little link to any specific changes in 3D joint kinematics.[22,23] In the work of Willson and Davis, the FPPA measured by 2D methods reflected only 23-30% of variance of 3D values.[23]

Despite evidence regarding the reliability and validity of 2D video analysis for functional tasks, research on the use of this type of analysis during running is limited. McClay and Manal conducted one of the initial studies comparing 3D and 2D analyses in running gait analysis using 18 middle-aged recreational runners.[19] While examining rearfoot variables, the researchers found that although the difference between peak 3D and 2D eversion angular displacement and eversion angular velocity was negligible, there were significant differences in eversion at toe-off and time to peak eversion, especially when the foot was abducted greater than 10 degrees.[19] However, to the authors' knowledge, no studies have evaluated the concurrent validity and reliability of 2D video analysis at the hip and knee during treadmill running. Therefore, the purposes of this study were to assess the concurrent validity of 2D video analysis of the frontal plane kinematic variables of contralateral pelvic drop, peak hip adduction angle and peak knee abduction angle bilaterally during treadmill running, as well as to assess the intra-rater reliability of 2D video analysis. The first tested hypothesis was there would be a moderate correlation in all three kinematic variables between 2D and 3D software, indicating the concurrent validity of the 2D software. The second hypothesis was there would be excellent intra-rater reliability in the utilization of the 2D software. If found valid and reliable, there may be great potential for utilization of the 2D gait analysis software in the examination of running kinematics in the frontal plane. Furthermore, this finding would directly benefit current and future clinicians that perform screening and retraining for potentially faulty biomechanical patterns with affordable and feasible software.

METHODS

Participants and Setting

Twenty-four collegiate cross-country runners (male n = 14, age 20.2 ± 1.2 years; female n = 10, age 19.5 ± 1.5 years) had their running kinematics assessed. (Table 1) Informed written consent was obtained from each subject in accordance with the protocol approved by the Cincinnati Children's Institutional Review Board and the rights of the subjects were protected throughout the study. Data collection took place immediately before the fall cross-country season in a laboratory setting. Subjects were excluded if they were currently under medical supervision and not fully cleared to participate in a structured running program. Inclusion criteria consisted of current participation on a collegiate cross-country team and self-reported free from pain during testing. Weekly mileage was greater than 30 miles for all subjects with an average of 64 ± 18 miles/wk.

Treadmill Running Protocol

Frontal plane thorax, pelvis, thigh, and shank motion were captured during a self-selected speed (SS) on a custom built treadmill (2.12 m length by 0.91m width running surface). The criteria for determining SS was initially determined by asking each subject what pace he/she would select for an easy 20-min run, as done in Ford et al.[26] The treadmill speed was blinded from the subject and adjusted, if requested by the subject, after a brief period of less than two minutes.

Table 1. *Characteristics of subjects included in the investigation*

	All (±*SD*) n=24	Males (±*SD*) n=14	Females (±*SD*) n=10	p-value
Age (years)	19.9 (1.3)	20.2 (1.2)	19.5 (1.5)	0.22
Weekly Mileage (miles)	64.4 (17.9)	76.6 (11.7)	47.2 (8.0)	<0.001
Height (cm)	167.8 (23.1)	177.8 (6.7)	153.9 (30.5)	0.009
Mass (kg)	59.7 (6.6)	64.0 (4.2)	53.7 (4.3)	<0.001
BMI	20.0 (1.4)	20.1 (1.0)	19.9 (1.8)	0.724

BMI= Body mass index

Following the speed selection, the total acclimation period for each subject was approximately three to five minutes. Although Lavcanska and colleagues found that six minutes were required for gait to normalize for consistency of measurements, their subjects were inexperienced with treadmill running.[27] Riley et al utilized an acclimation period of three to five minutes and found that mechanics on the treadmill could be generalized to overground running.[28] The subjects in the current study were collegiate runners and all had previous experience in treadmill running. A one-minute trial was collected at each speed, simultaneously using both the 3D and 2D methods.

3D Motion Analysis of Frontal Plane Variables

Reflective markers were placed on the spinous process of the seventh cervical vertebra, sternal notch, sacrum, and bilaterally on the acromio-clavicular joint, upper arm, lateral epicondyle of the elbow, mid-wrist, anterior superior iliac spine (ASIS), greater trochanter, middle of distal femur just proximal to the superior pole of the patella, medial and lateral femoral condyles, tibial tuberosity, lateral knee joint line, middle of the distal tibia, and medial and lateral malleoli.[29] (Figure 1) These markers were utilized to calculate three-dimensional angular displacement of the pelvis, thigh and shank during treadmill running. Three-dimensional marker trajectories were collected with Cortex software (Motion Analysis Corporation, Santa Rosa, CA) using a motion analysis capture system with 10 digital cameras (Eagle cameras; Motion Analysis Corporation), collected at 240 Hz. Twenty consecutive steps were analyzed for each subject. Three-dimensional kinematic variables were determined using Visual3D software (C-Motion, Inc., Germantown, MD). Specifically, knee and hip angular displacements were calculated as the motion of the distal segment relative to proximal segment. Pelvic motion was calculated as the motion of the segment relative to the global laboratory coordinates. Maximum and minimum kinematic data for pelvic, hip, and knee motions in the frontal plane were identified during the stance phase (treadmill contact to toe-off) for each consecutive step and then averaged.[26,30]

2D Motion Analysis of Frontal Plane Variables

During self-selected running trials, 2D kinematics in the frontal plane were assessed using Dartfish Motion Analysis Software (Dartfish, Fribourg, Swizerland). Video capture for 2D analysis was conducted concurrently during the 3D Motion Analysis data collection. The three variables of interest included peak contralateral pelvic drop angle (CPD), peak hip adduction angle (HADD), and peak knee abduction angle (KABD). Five trials of 2D analysis and 30 trials of 3D analysis were taken for both

Figure 1. *Marker Set for 3D Running Kinematic Assessment (used with permission of the International Journal of Sports Physical Therapy)*

the left and right lower extremities of each subject during midstance, where peak HADD, CPD, and KABD have been reported to take place in the literature.[5,11,13,31] Pilot data from the lab demonstrated that the means of five trials under 2D analysis correlated well with the means taken from 30 trials for five different subjects, further validating the five trial method used for the 2D data. In addition, Lee and Farley found that the stance limb reached maximum compression at approximately the same time as the center of mass (COM) reached its lowest position near midstance.[32] Since the peak 3D values and minimum COM values also occurred approximately at the same time in the current study, the minimum COM was determined as the point in the running cycle when the stance leg reached maximal compression or knee flexion. During each trial, the three variables were measured and calculated. (Figure 2) CPD was calculated as the angle subtended by one line connecting the ASIS with the stance and swing limb and a second line drawn perpendicular to the stance limb ASIS. The measurement was then subtracted from 90 degrees. The HADD was defined as the angle subtended by one line connecting the anterior superior iliac spines (ASISs) bilaterally and a second line connecting the ASIS of the test limb with the midpoint of the tibiofemoral joint. Finally, KABD was calculated as the angle subtended by a line connecting the ASIS of the stance limb with the midpoint of the tibiofemoral joint and a second line connecting the midpoint of the tibiofemoral joint and the bisection of the medial and lateral malleoli, similar to methods employed by Hollman and collegues.[20] The KABD evaluated in this study is also similar to the measurements of frontal plane projection angle (FPPA) that have been used widely in the literature.[22,23]

Statistical Analysis

Concurrent validity of 2D motion was examined by comparing frontal plane angles derived from 2D kinematic analysis to measurements obtained using a 3D motion analysis system. Pearson Product Correlation Coefficients were used to determine the relationship between the 2D and 3D measurements of frontal plane kinematic variables of interest; specifically CPD, peak HADD, and peak KABD. These statistical analyses were used to assess the concurrent validity of the 2D measures obtained with the Dartfish Software. Second, the intra-rater reliability of the 2D assessment was examined. The intra-rater reliability of the 2D software was performed using Intra-Class Correlation Coefficients (ICC). Intra-rater reliability was evaluated by having the evaluator perform a test-retest analysis of the same frames one week apart. Pearson Product Correlation Coef-

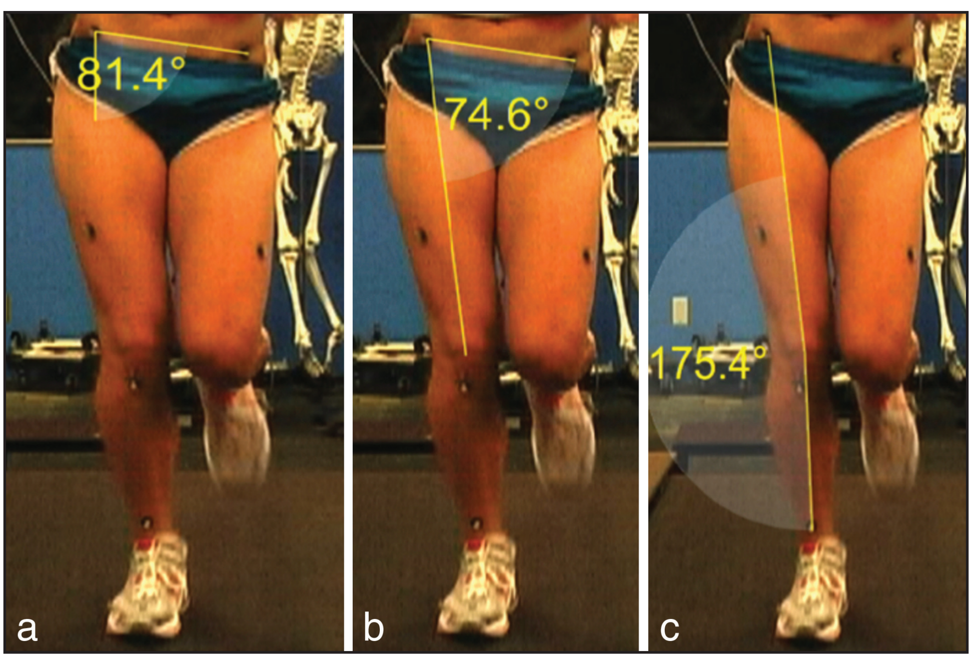

Figure 2. *2D Measurements of a) Contralateral Pelvic Drop, b) Hip Adduction, and c) Knee Abduction during Midstance*

ficients and Bland Altman plots were also utilized to identify the relationship between each of the kinematic frontal plane variables of interest.[33]

Results

The 2D Dartfish Testing Method for frontal plane kinematic variables demonstrated high reliability. Intra-rater reliability for peak HADD (ICCs: 0.951-0.963), peak CPD (0.958-0.966), and peak KABD (ICCs: 0.955-0.976) were excellent for bilateral lower extremities. (Table 2)

In terms of concurrent validity, Pearson Product Correlation Coefficients examining the relationship of 2D and 3D measures of peak hip adduction during running were moderately correlated on the left (0.539; $p = 0.007$) and the right (0.623; $p = 0.001$) lower extremity. (Table 3) Regression analyses of the HADD data between the 2D and 3D methods yielded r^2 values of 0.388 for the right lower extremity and 0.291 for the left lower extremity. (Figure 3) Bland Altman plots confirmed there was no systematic shift between 2D and 3D analysis. (Figure 4 and Figure 5) There was not a significant correlation between 2D and 3D assessment of CPD, and there were inconsistent findings on KABD, as only one of the two limbs was correlated. (Table 3)

Table 2. *Intra-rater reliability: Test-retest reliability with a single tester during the stance phase of running*

Average Peak 2D Kinematics (in degrees)	ICC	
	Right	Left
Pelvic Drop	0.966	0.958
Hip Adduction	0.951	0.963
Knee Abduction	0.976	0.955

Finally, the 2D measure of CPD demonstrated a strong correlation to the 2D assessment of HADD on both the left (0.801; $p = 0.0001$) and the right (0.746; $p = 0.0001$) extremities. However, no strong correlations were found between the other variables.

Discussion

The purpose of this study was to examine the reliability and validity of 2D analysis of frontal plane kinematics during treadmill running. Although there have been comparisons between 2D and 3D methods in the analysis of knee valgus[18,22,23] and knee and hip flexion[24] in the literature, to the authors' knowledge this 2D method for hip and knee variables has not been compared to 3D kinematic assessments during treadmill running. Consistent with this study's hypothesis, the 2D analysis demonstrated excellent intra-rater reliability. The high reliability found in this study for the use of 2D video analysis to measure frontal plane kinematic variables of running performance confirms the consistency of angle measurements obtained by the same tester. This finding is consistent with reported intra-rater reliability of other dynamic movements using 2D motion analysis systems in the literature.[18,21,24,25]

In regards to validity, the tested hypothesis that there would be a moderate correlation between the frontal plane kinematics of CPD, peak HADD, and peak KABD was partially supported. There was a significant, moderate correlation found bilaterally between 2D and 3D methods for HADD for both male and female runners on the left and the right lower extremities. However, a significant correlation did not exist bilaterally between 2D and 3D motion analysis for the kinematic variables of CPD and KABD.

Table 3. *Means and Pearson Correlation Coefficients for frontal plane variables in the 2D and 3D analyses*

	Right				Left			
	2D in deg (SD)	3D in deg (SD)	Pearson Correlation Coefficient	p-value	2D in deg (SD)	3D in deg (SD)	Pearson Correlation Coefficient	p-value
Contralateral Pelvic Drop	4.6 (2.1)	5.2 (1.4)	0.333	0.401	4.3 (1.9)	5.7 (2.1)	0.194	0.364
Hip Adduction	11.2 (2.7)	14.0 (3.7)	0.623	0.001*	11.8 (2.7)	13.8 (2.5)	0.539	0.007*
Knee Abduction	2.3 (4.0)	4.5 (3.5)	0.158	0.460	1.3 (2.9)	5.3 (2.9)	0.541	0.006*

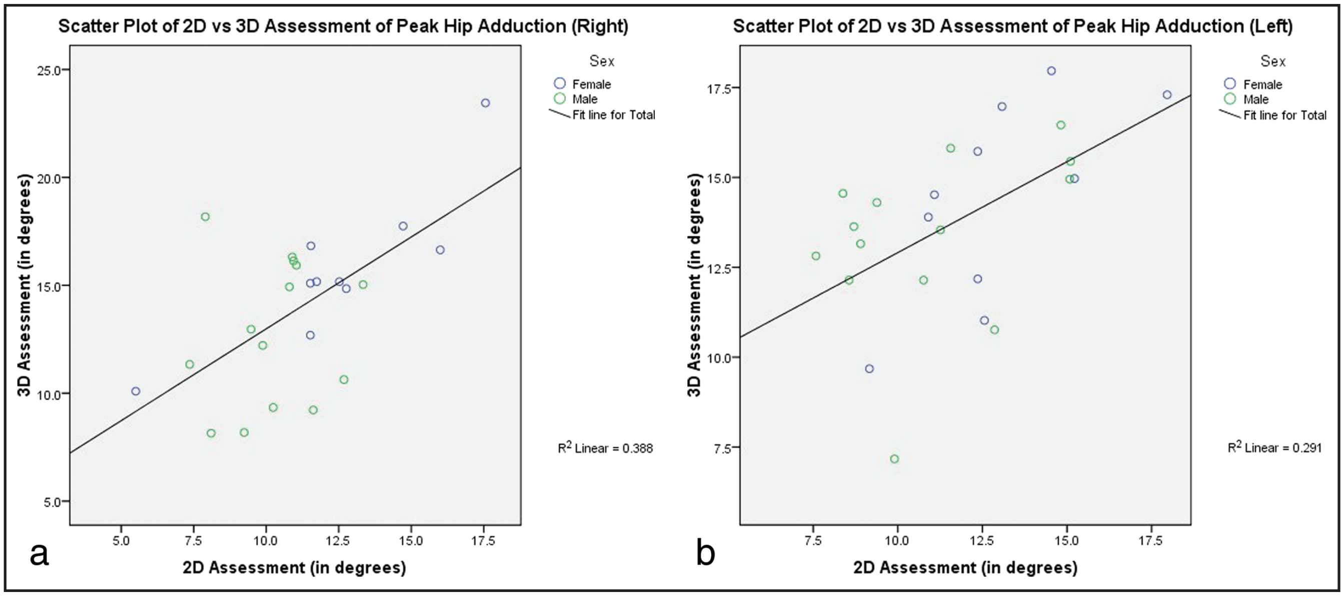

Figure 3. *Peak Hip Adduction Angle: 2D vs 3D. a) Right Leg, b) Left Leg*

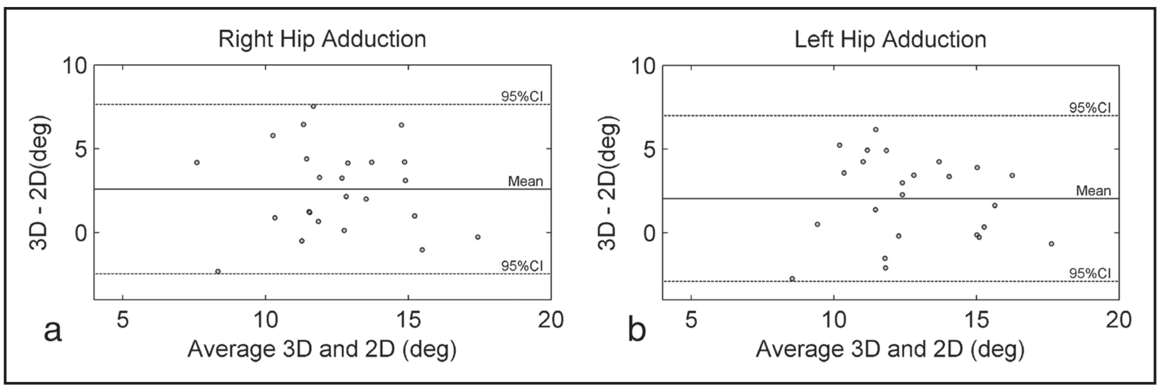

Figure 4. *Bland-Altman Plots for Hip Adduction. a) Right Leg, b) Left Leg*

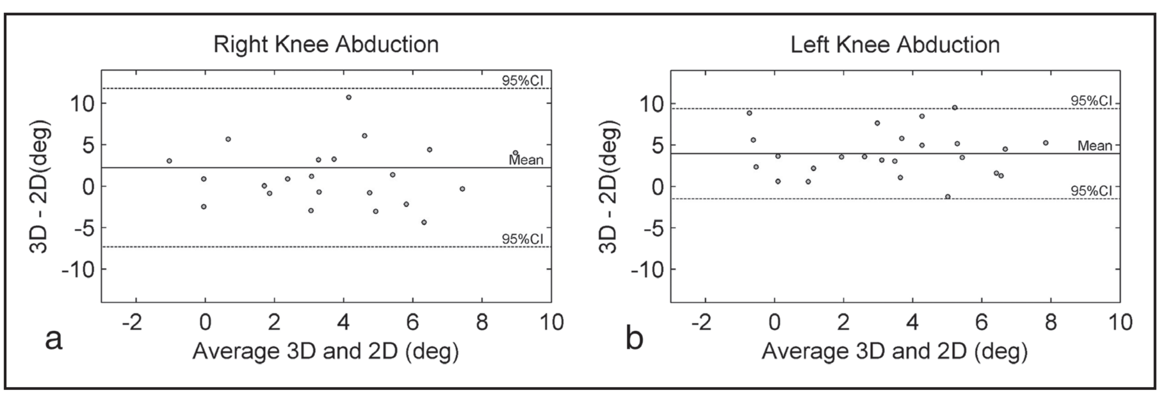

Figure 5. *Bland-Altman Plots for Knee Abduction. a) Right Leg, b) Left Leg*

To date, no other studies have examined the concurrent validity of the 2D kinematic variable of peak HADD to 3D methods. The HADD has been previously established as an integral kinematic variable to examine in runners. Previously described hip adduction and hip internal rotation in weight bearing resulted in the medial displacement of the knee joint relative to the foot.[16] This leads to tibial abduction and increased foot pronation, resulting in dynamic genu valgus.[16] Based on this pattern of linked abnormal movement patterns, excessive HADD has been previously linked to running-related injuries such as PFPS[8,10,11], ITBS[1,12], and tibial stress fracture.[14,15] With regard to PFPS, Dierks and colleagues evaluated 20 male and 20 female recreational runners and found a link between increased HADD and weak hip abductor strength in runners with PFPS symptoms.[11] Similar findings were found by Noehren and colleagues in a cohort of female runners with PFPS as compared to healthy controls.[8] In addition to increases in peak HADD, the PFPS group also demonstrated increased peak hip internal rotation compared to the control group.[8] With regards to ITBS, Ferber and colleagues examined differences in competitive, female runners with a history of ITBS as compared to healthy, mileage and age-matched controls revealing increased peak HADD, peak knee internal rotation, and greater peak rearfoot invertor moment in the history of ITBS group.[12] Retrospectively, HADD was also found to be one of the three variables of choice in correctly predicting a history of tibial stress fracture in a cohort of adult female distance runners.[15]

Clinically, strengthening and neuromuscular re-education protocols used to treat runners with these diagnoses have led to decreases in HADD in addition to improving pain and function.[6,7,34,35] Willy and Davis performed hip abduction and hip external rotation strengthening and movement education specific to the single leg squat in healthy, female runners and reported significant decreases in HADD, CPD, and hip internal rotation during the squatting movement. However, these improvements in squatting biomechanics were not carried over into running, potentially suggesting that movement training and strengthening employed by the authors was not specific enough to running.[35] To that end, Noehren and colleagues investigated the effect of gait training, specifically, hip adduction feedback, in male and female recreational runners with PFPS. Following 8 sessions of visual gait re-training, subjects reduced their HADD by 23% (5 degrees) and had significant improvements in pain and function [7]. Collectively, this suggests that HADD is an important kinematic variable to examine in individuals with similar running-related injuries and may be an important variable for further research investigations.

Although the results of this study support the use of 2D video analysis for analyzing HADD in the clinic, consistent significant correlations were not found in the variables of CPD and KABD between the 2D and 3D methods. Similar studies have evaluated the validity of 2D software in the measurement of the FPPA.[18,21–23] Willson and Davis' protocol used for the FPPA measurement was similar to this study's measurement of KABD.[23] However, this study utilized the midline of the tibiofemoral joint instead of the distal midpoint of the femur for the angle measurement. Mclean and colleagues investigated side step and side jump movements in healthy male and female collegiate basketball players.[18] The authors confirmed that the 2D knee FPPAs were inherently influenced by hip and knee joint rotations in all three dimensions. Between subjects, 2D camera and 3D data correlated well for the side step ($r^2 = 0.58$) and side jump ($r^2 = 0.64$). Within subjects, 2D camera and 3D data correlated moderately for the side step ($r^2 = 0.25 \pm 0.19$) and side jump ($r^2 = 0.36 \pm 0.27$).[18]). However, it should be mentioned that the values for knee abduction angle in Mclean and colleague's study were significantly higher than the values for knee abduction angle found in the current study. Similarly, Wilson and Davis analyzed the FPPA during SL squats in females with and without PFPS. Findings suggested that the FPPA values during single-leg squats were associated with increased hip adduction ($r = 0.32$ to 0.38, $p < .044$) and knee external rotation ($r = 0.48$ to 0.55, $P < .001$) across activities.[23] However, the tested theoretical construct that the 2D analysis of FPPA could quantify 3D joint rotations was not supported. Similarly, Olsen and colleagues assessed the effects of a neuromuscular training program in a cohort of healthy females during a step down task and did find changes in FPPA. They concluded that 2D changes were not significantly associated with any specific change in 3D joint kinematics.[22] Together, the current findings are consistent with the findings of these previous studies that 2D methodology does not adequately capture 3D knee abduction motion.

To the authors' knowledge, no studies have previously evaluated the correlation of CPD between 2D and 3D methods in treadmill running and/or other dynamic functional tasks. CPD has been formerly correlated with hip extensor and hip abductor weakness in runners.[10,26] The current study did not find a significant correlation of this variable between the 2D and 3D methods. The differences in data collection frame rates between the 2D system that sampled at an effective rate of 60Hz, compared to the faster 240Hz frame rate of 3D systems may explain the non-significant relationship. For instance, 2D CPD had consistently lower magnitudes of motion compared to the 3D CPD which suggest a sampling rate error could exist at the slower frame rates.[36] Since the averages for CPD were smaller values than the averages for HADD, the CPD averages would have been more affected by the systematic difference in frame rate. However, there was a significant correlation between CPD and HADD on both the left (0.801; $p = 0.0001$) and the right (0.746; $p = 0.0001$) side. From a kinematic standpoint, Powers suggested that contralateral pelvis drop during single-limb support may cause a shift in the center of mass away from the stance limb in the presence of hip abductor weakness.[16] In order to compensate, an individual may shift their center of mass over the stance limb through excessive hip adduction and internal rotation, potentially resulting in a knee valgus moment.[16] In the literature, female recreational athletes with and without PFPS were shown to demonstrate both excessive hip adduction and CPD during a stepping task.[10] Furthermore, interventions geared toward improving altered hip biomechanics, have resulted in decreases in both HADD and CPD.[10,22,35]

Based on the findings of the current study, 2D HADD may serve as a valid and reliable measure for one clinician to take when performing 2D running video gait analysis due to its concurrent validity to 3D methods and excellent intra-rater reliability. In addition to being linked to numerous running-related injuries-[1,8–10,12–15] it has been well-correlated to hip weakness and CPD.[6,7,26,35] The current study further supports the strong association between the variables of CPD and HADD. Since CPD and KABD were not well-correlated to 3D measurements, using the HADD as a means to predict hip weakness, potential running-related injuries, and track progress through strengthening and movement education programs through 2D video analysis may be more efficacious. The ease of use and cost-effectiveness of the 2D video analysis system enhances its potential for injury prediction, prevention, and rehabilitation

This study has several limitations. First, all running analyses in the current study were performed on a treadmill, which may not be generalizable to overground running. However, research by Riley and colleagues concluded that treadmill gait was qualitatively and quantitatively very similar to overground gait and subtle differences found between the two in terms of kinematics were generally within the normal variability of gait parameters.[37] The benefit of treadmill analysis is that it is used to standardized running conditions across subjects.[26] Second, it is difficult to substitute 2D measurements for the accuracy and magnitude of the 3D joint rotations during running and other dynamic movements. The current study analyzed the means of 5 trials of each subject's frontal plane kinematic variables in midstance using the 2D software. However, the 3D means of peak CPD, KABD, and HADD were calculated from 30 trials. To further validate the methodology used to calculate 2D means, the authors performed a pilot study on five randomly-selected subjects. The means of the 30 trials of all three frontal plane variables in the pilot study correlated well with the means taken from the five trials for each subject in the current study, further validating the protocol of this study.

Future research examining 2D video analysis of running biomechanics should utilize a larger sample of male and female participants of varying running abilities, mileage levels, and ages. In addition, the studies should include individuals with lower extremity musculoskeletal dysfunction and running-related injuries to expand the generalizability to populations typically seen in the clinic. Analyses of the validity and reliability of sagittal plane kinematic variables and frontal plane kinematic variables of the lower shank and foot would be useful in evaluating the clinical utility of the 2D video analysis software. Future directions of research should include exploring gender differences in frontal and sagittal plane kinematic variables evaluated by the 2D software. Finally, a relationship between hip weakness and altered biomechanics during running has been reported in the literature.[26,38] Research on movement education and strengthening programs have resulted in positive outcomes in improving these abnormal mechanics, increasing strength, decreasing pain, and improving function in runners.[6,7,35] However, more robust studies utilizing a comprehensive approach of neuromuscular training, plyometrics, core and proximal strengthening, and long-term gait retraining using 2D software are required to further evaluate the rehabilitative potential of such strategies for injured runners.

Conclusion

In conclusion, this study identified a moderate correlation in maximum HADD in both extremities of male and female collegiate runners between 2D software and 3D analysis, partially supporting the concurrent validity of the 2D analysis system. No significant correlation was found bilaterally between the two motion analysis systems regarding to CPD and KABD. In addition, the excellent intra-rater reliability found in the current study suggests that the 2D software can accurately be used to examine changes in a patient's running mechanics from the initial evaluation through the interim assessments by the same evaluator. Based on these results, clinicians utilizing 2D software may have improved confidence regarding describing HADD during clinically based running gait assessments when the 3D "gold standard" software is unavailable. Over all, this study serves as a strong foundation for future research in the utility of 2D video analysis software in accurately examining and treating injured runners for both clinical and research purposes.

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